Investigation of atomic processes of high-Z ions in plasmas for EUV applications

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Introduction

- Future EUV lithography demands development of higher power (>200W), shorter wavelength (6.5nm) EUV sources.
- Basic research of the plasma atomic process is indispensable for the better understanding plasma emission to obtain high efficiency.
- The method for modeling atomic processes developed for Sn source is extended to investigate properties of new atomic transitions rather than 4d-4f, which is applicable to λ=6.5nm sources.

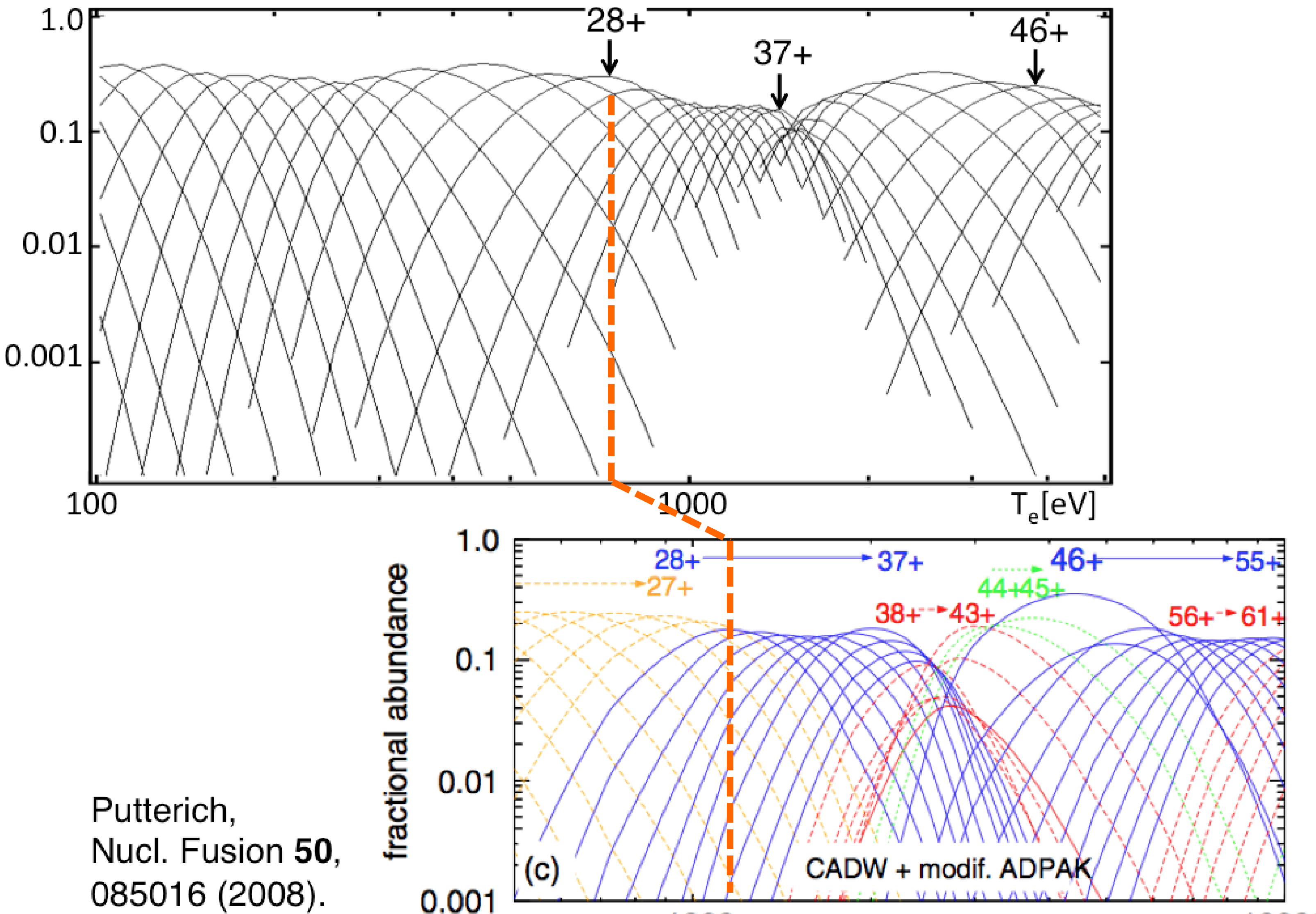
Contents

- Improvement of the atomic kinetics code since Dublin meeting through nLTE code comparison workshop.
- Numerical experiment of light sources at λ=6.5nm using Kr and Mo plasmas.

Benchmarking atomic kinetics code

- Atomic kinetics code is required for analysis of emission and calculation of radiation hydrodynamics of EUV sources.
- However, considerable difference was seen between result of each atomic kinetics codes.
- Difficulty of the modeling arises from ;
  - Complex atomic processes.
  - Spectrum from plasmas largely depends on hydrodynamics and radiative transfer, causing comparison between theory and experiment difficult.

• Significant difference between codes is seen in calculated fractional abundance of W.



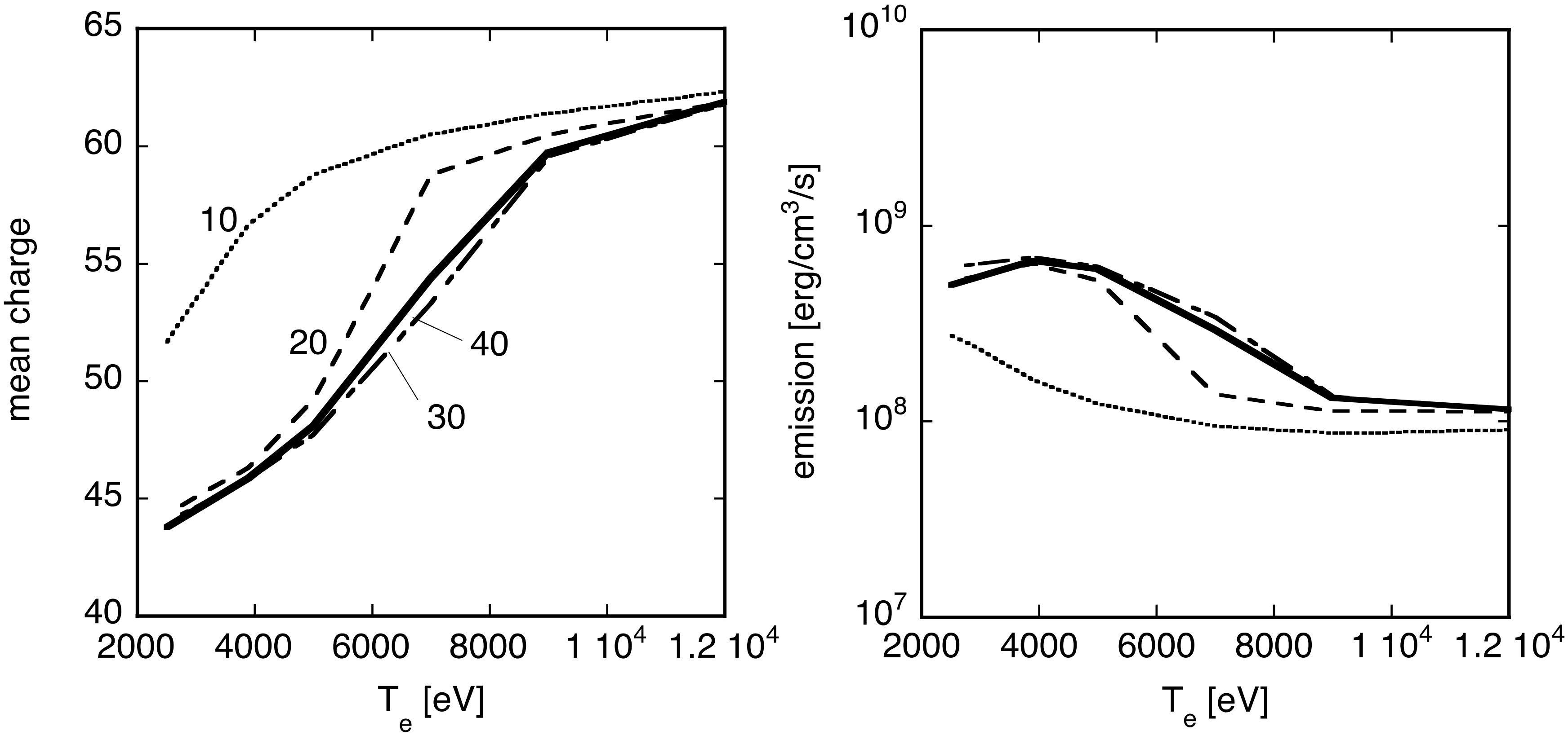
Putterich, Nucl. Fusion **50**, 085016 (2008).

nLTE kinetics code comparison workshop

- Participants bring result of atomic kinetics code for test problems and compare each other.
- Tungsten is chosen as a typical high-Z atom.
- 7 workshops since 1996, recently December 5-9 2011.

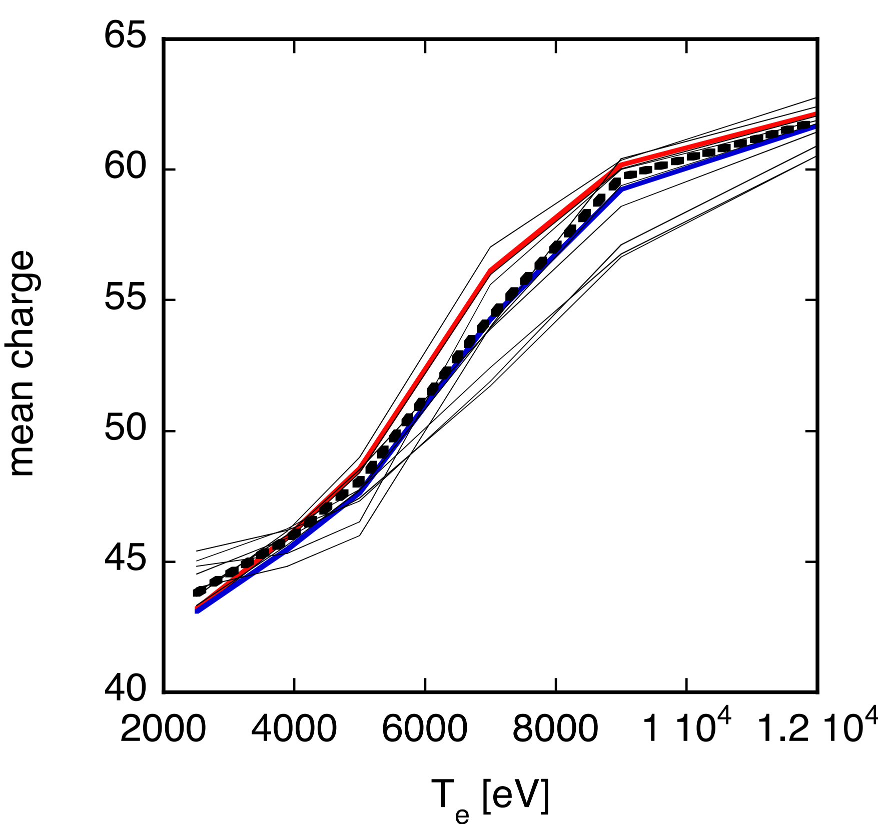
Result of W calculations using JATOM code

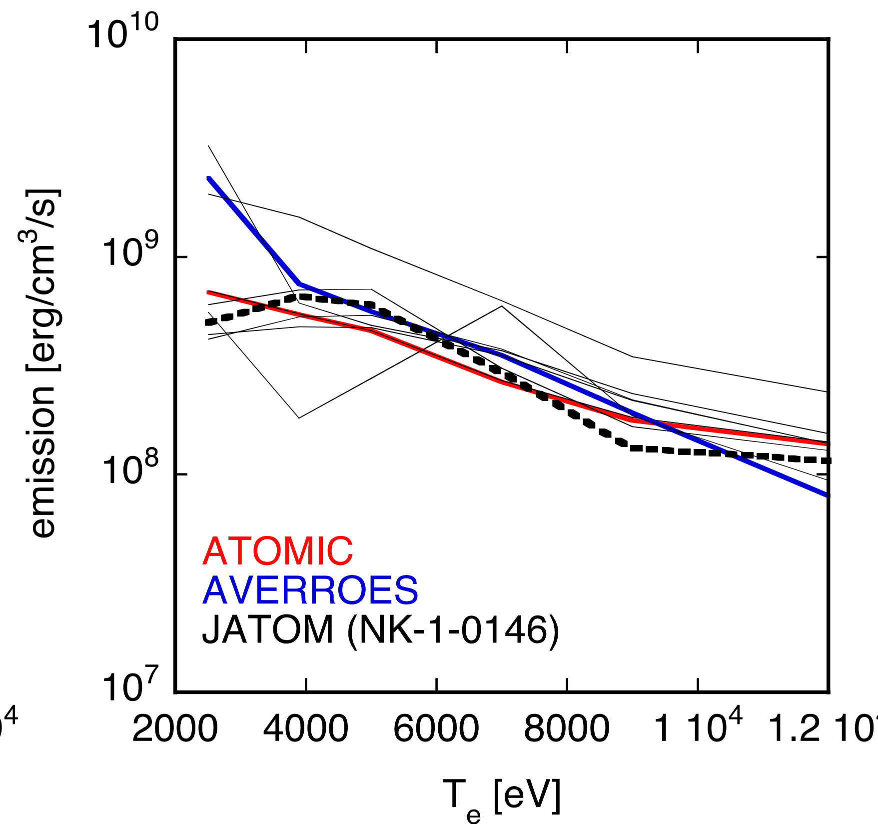
- Based on calculated atomic data using HULLAC.
- Size of the model (number of levels) is parameterized and increased until mean charge and emission converge.



Present status of JATOM code

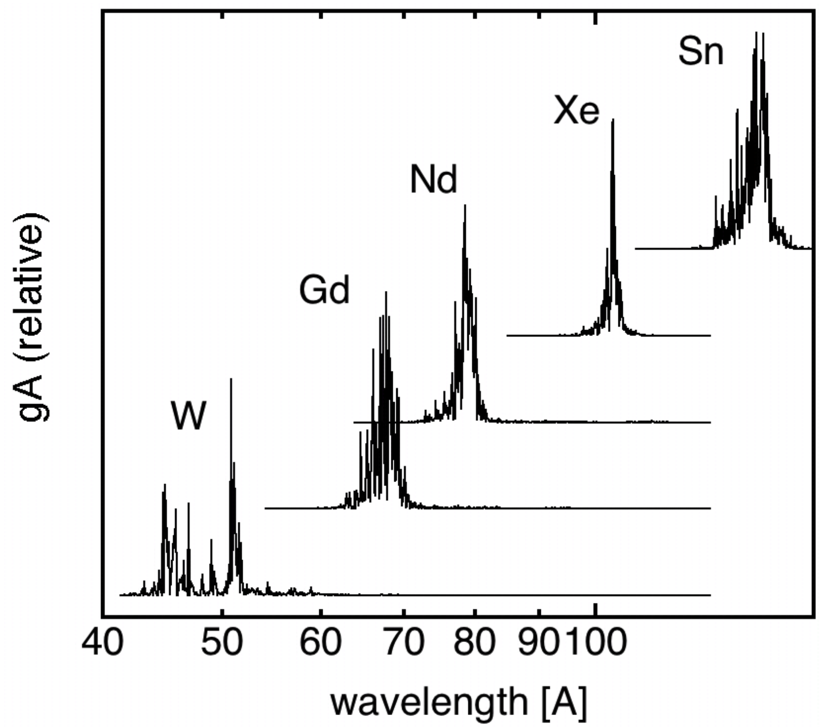
- Mean charge and radaitive power loss agrees well other calculations; this allows one to make accurate prediction of level population and emission spectrum of any multiple charged ions with JATOM code.





Numerical experiment of Kr to Mo plasmas

- Short wavelength source may be useful for future EUV lithography.
- 4d-4f transition is scalable, and emission at λ=6.5nm can be realized using Gd/Tb plasmas.

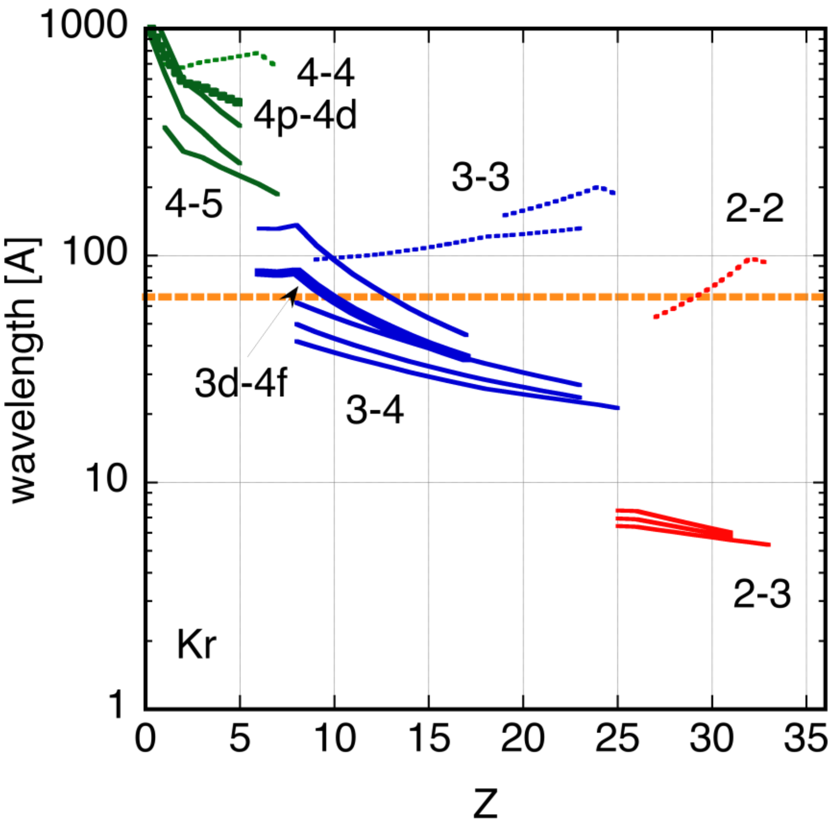


- Gd/Tb targets requires higher temperature (≈100eV).
- Rare earth target is expensive and has high melting temperature.

3d-4f transition of near Ni-like Kr ions

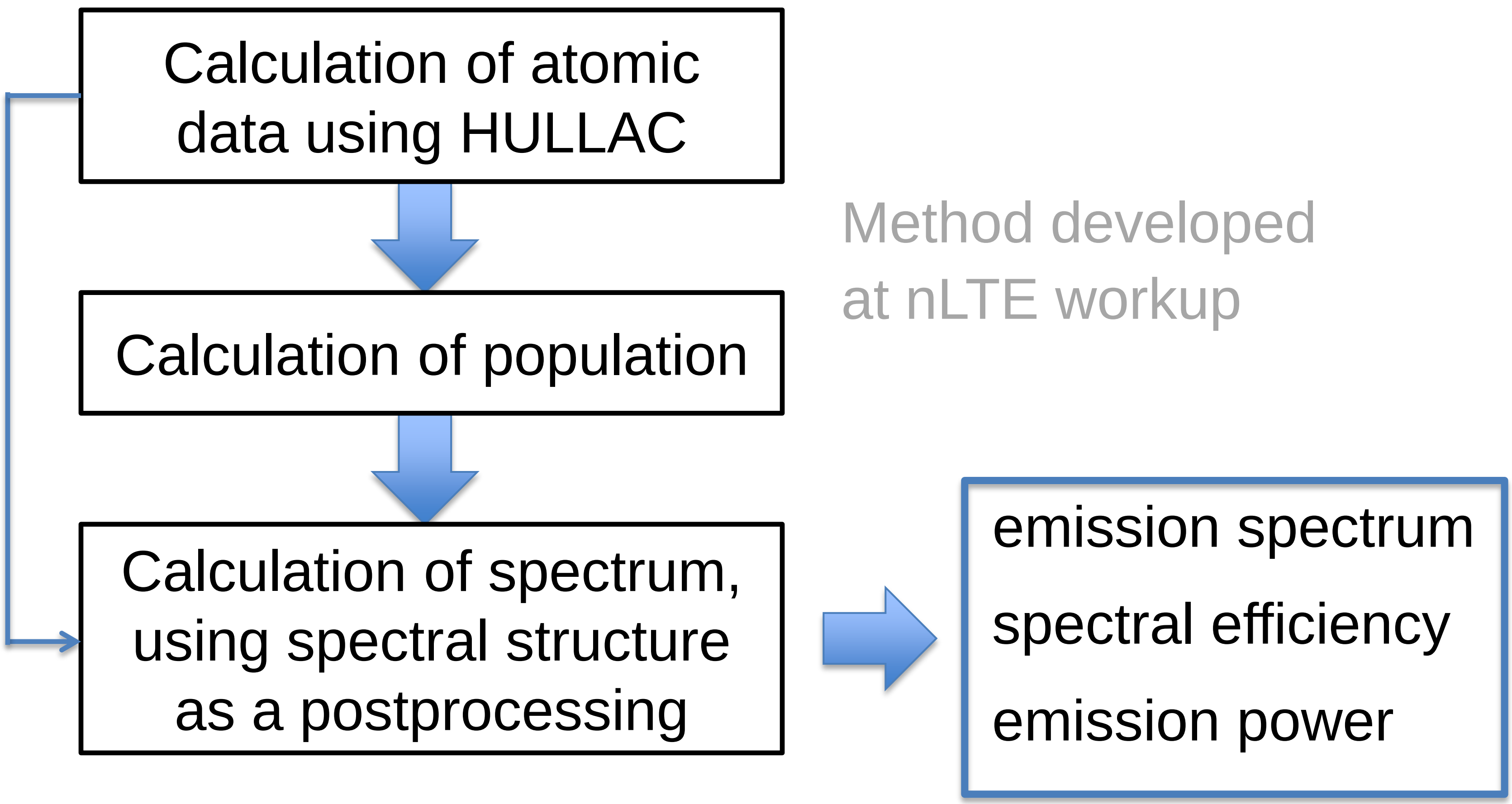
- Strong emission is obtained from resonance lines; depending on temperature, an ion can be a light source at several different wavelength region.

- Near Ni-like (Kr^{10+}) ion may have strong emission at λ=6.5nm through 3d-4f transitions.



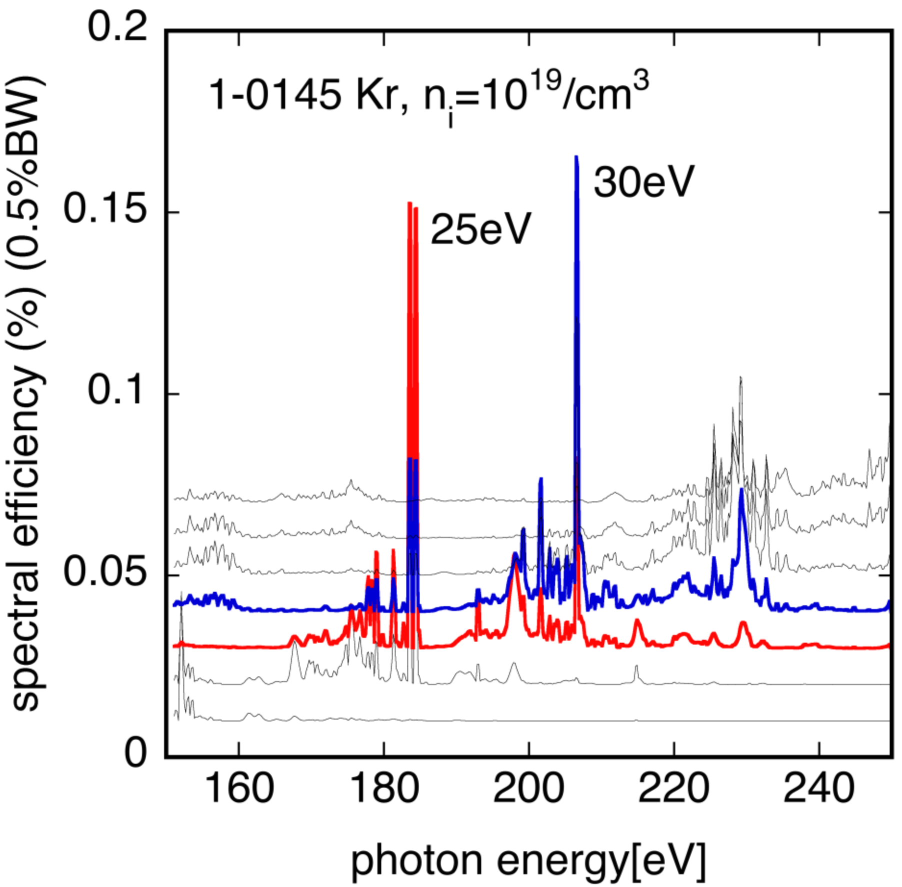
Numerical experiment of plasma light sources

- Emission from Kr is investigated using a method similar to that used for the analysis of Sn plasmas.
- Emission is estimated using simple plasma model.

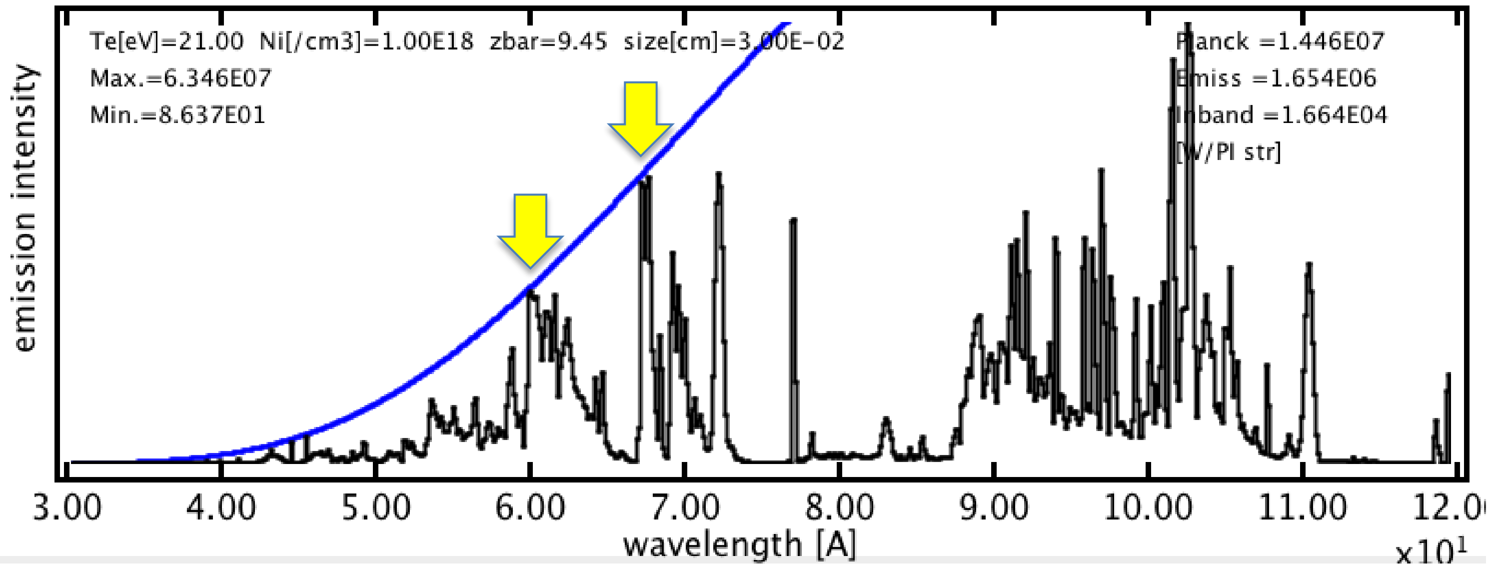


Property of emission from Kr ions

- Spectral efficiency of Kr shows strong peak near 180 and 200eV, arising from Co-like Kr^{9+} and Fe-like Kr^{10+} ions.



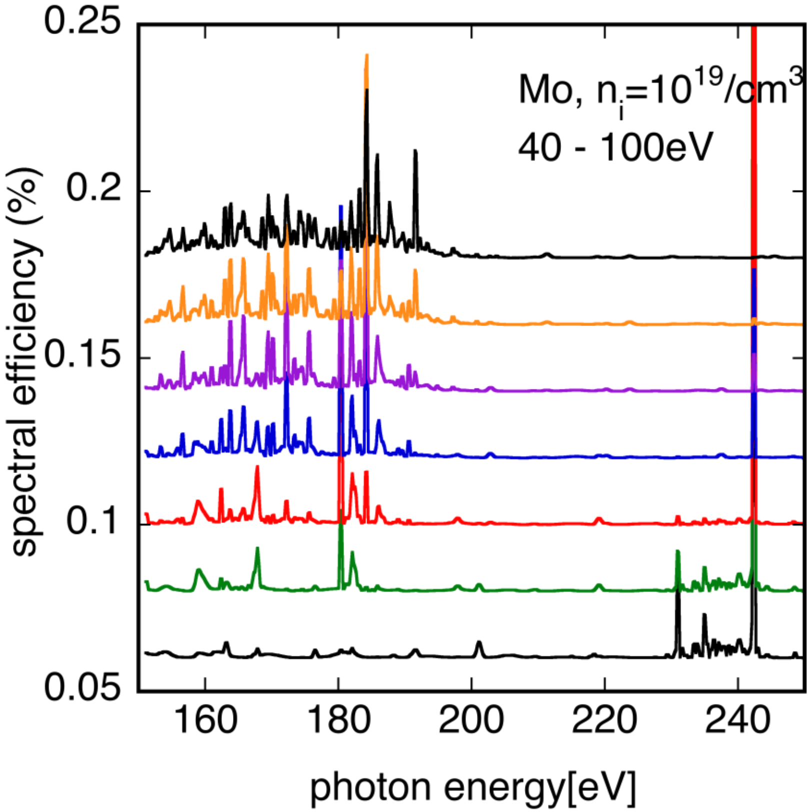
- However, calculated spectra from LTE plasma shows peaks near λ=6.5nm are not very strong.

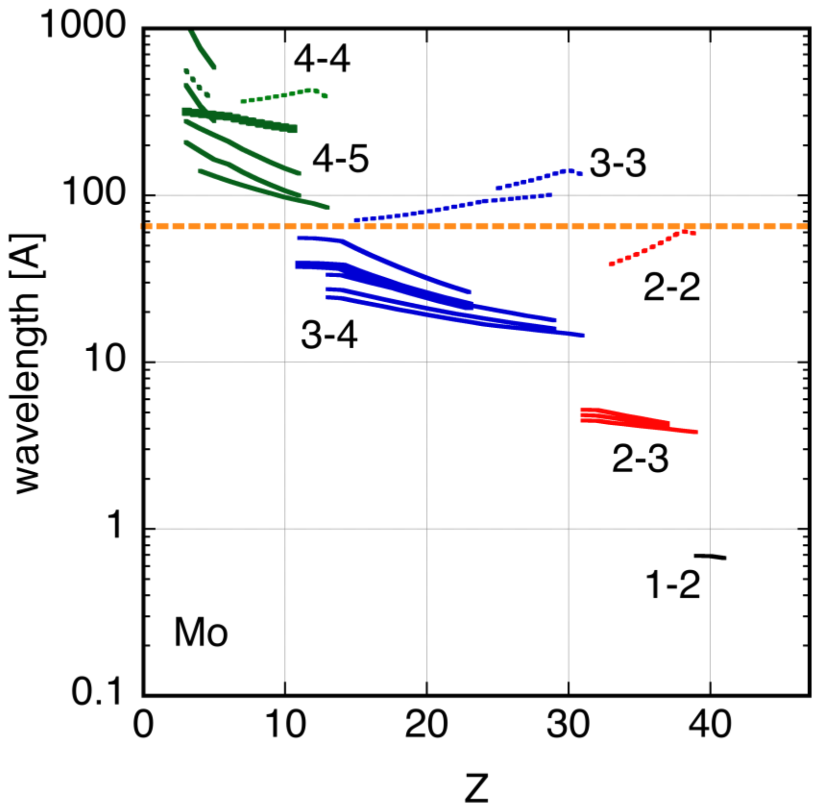


Co- and Fe-like ions are populated at rather low temperature (25-30eV), which is too low to have strong emission in 190eV region.

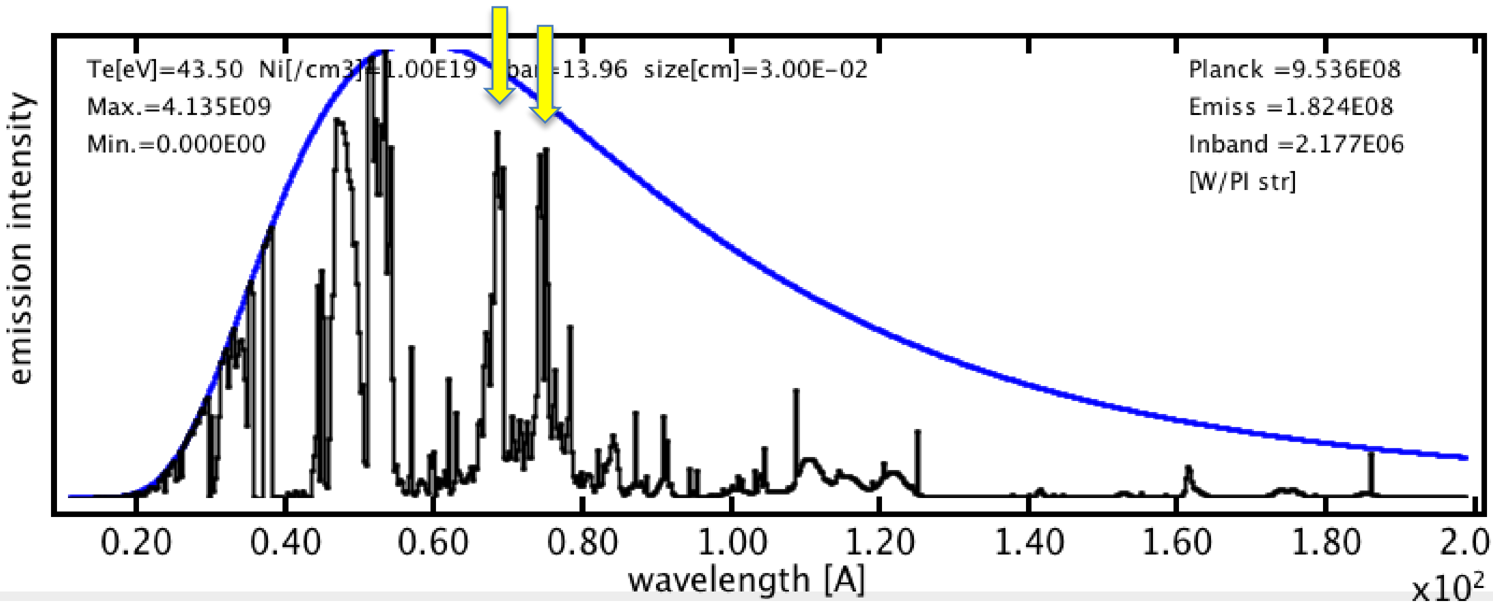
Property of emission from Mo ions

- Spectral emissivity is investigated for elements with Z= 36 – 48 to find Mo ion shows strong emission at 190eV, which arises from 3-3 transitions.





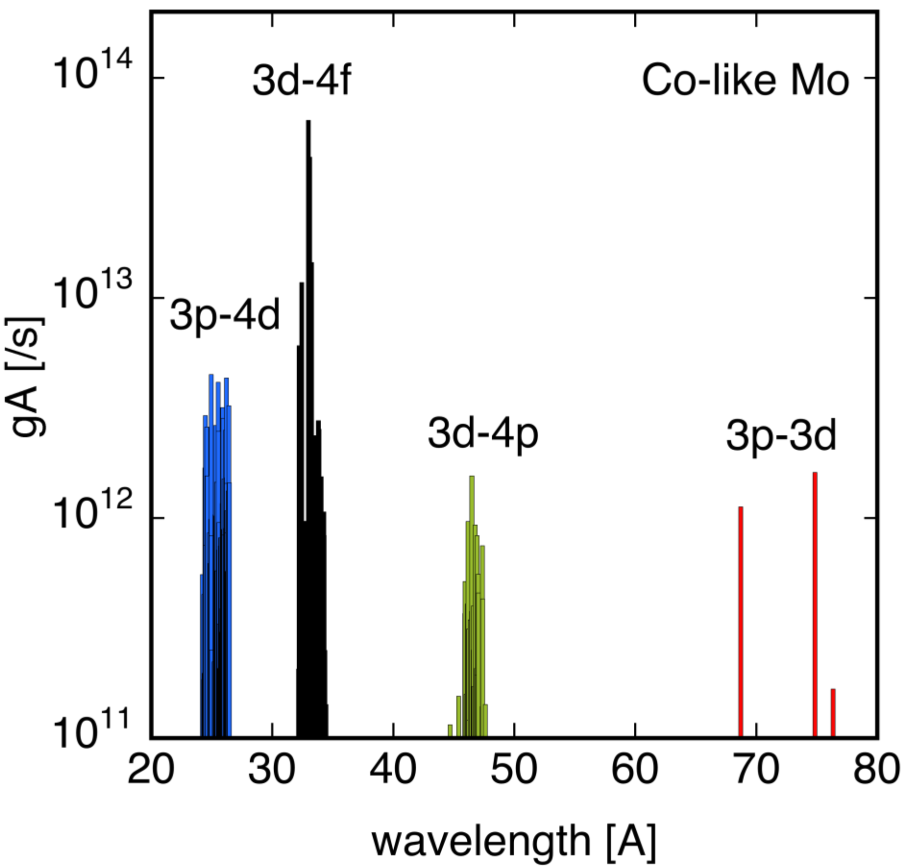
- LTE spectra shows double peak at 6.9 and 7.5nm, which arises from $3d^9$-$3p^5 3d^{10}$ transition of Co-like Mo.



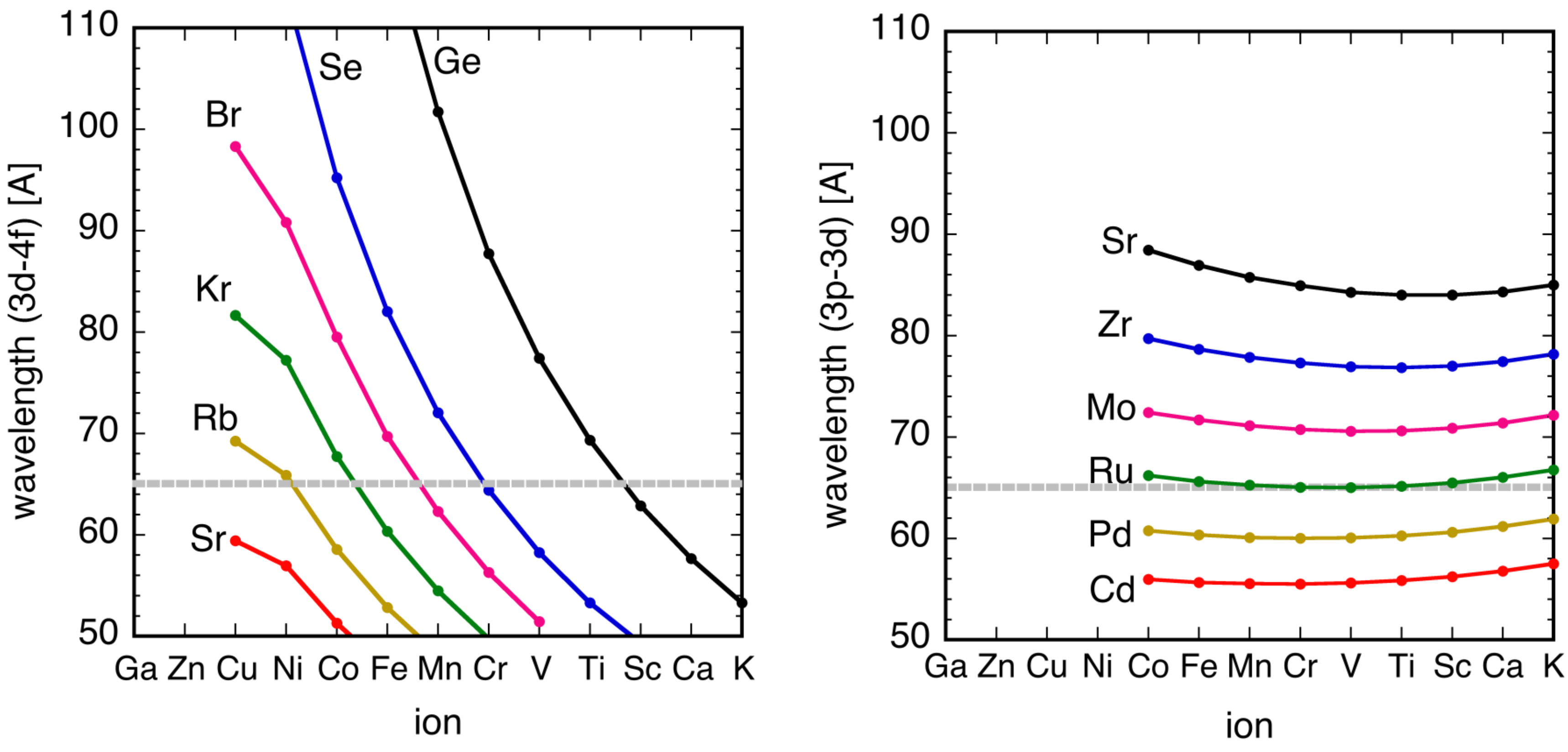
transition	NIST	HULLAC
3/2-1/2	6.9596	6.8711
5/2-3/2	7.5869	7.4281

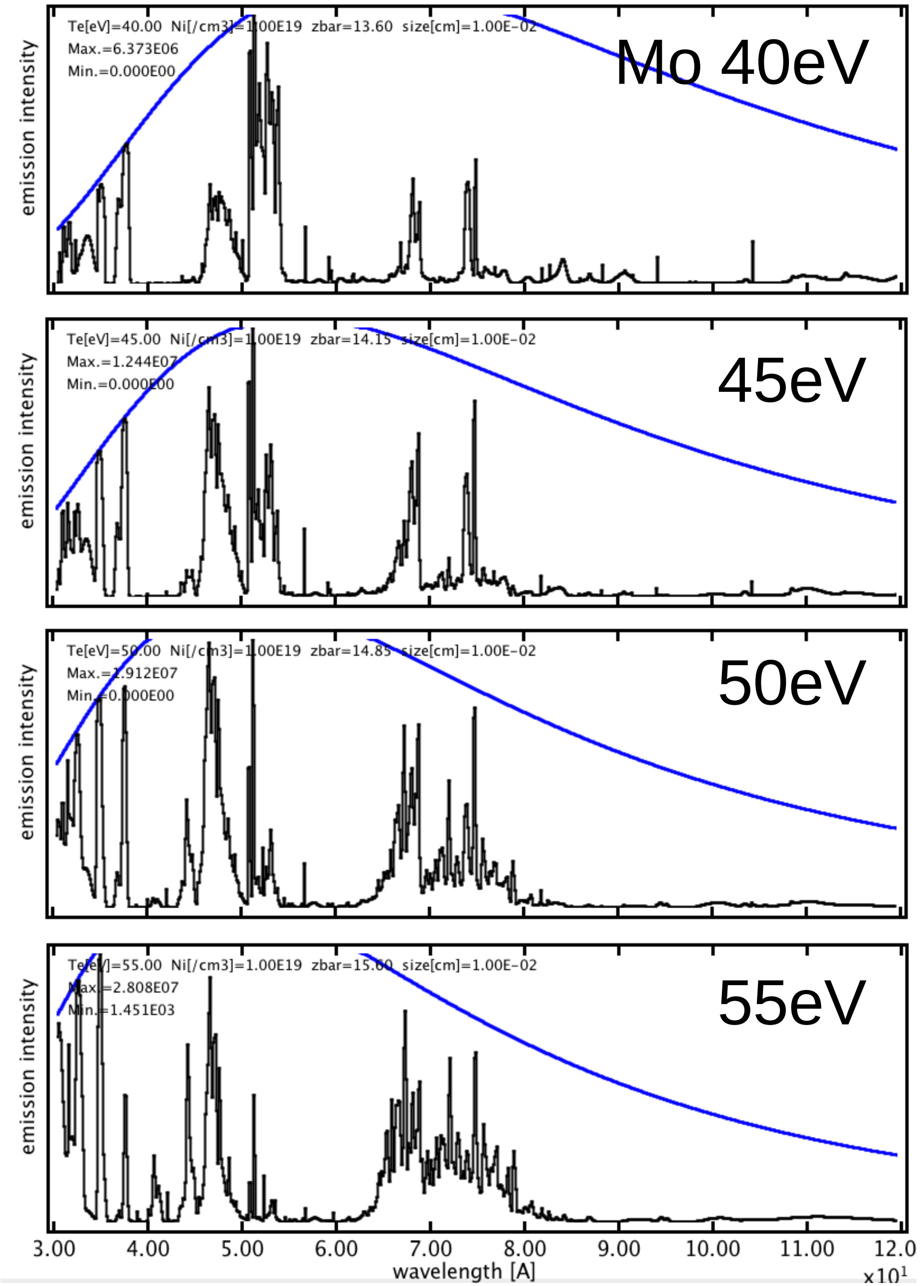
- Calculated wavelength differs 2% from NIST database.

- Emission of 3p-3d transition is strong, because even gA is small, wavelength is near the peak of Planck radiation for the temperature condition, where Co-like ion has a large abundance.



- 3p-3d transition has a property similar to 4d-4f transition. Wavelength is almost constant over wide range of charge states and becomes shorter as the atomic number increases.

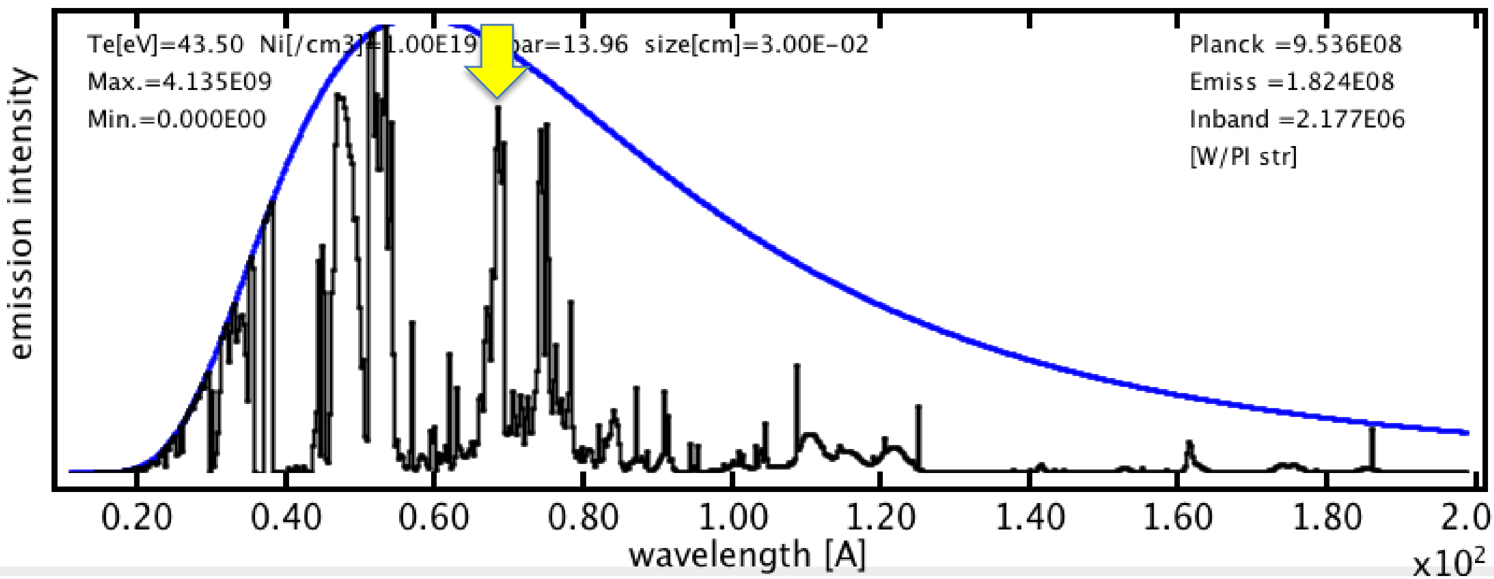




- Spectrum becomes broader as charge state increases beyond Co-like ion.

$n_i = 10^{19}/cm^3$

- Optimization in limited parameter space shows Mo plasma with T_e=43eV, n_i=10^{19}/cm^3, and plasma size=0.3mm, 10^6W/πstr of EUV power at 6.5nm (0.5%BW) is obtained with spectral efficiency of 1%.



- LTE is assumed.
- Total output power for 10ns, 10kHz pumping is 100W.

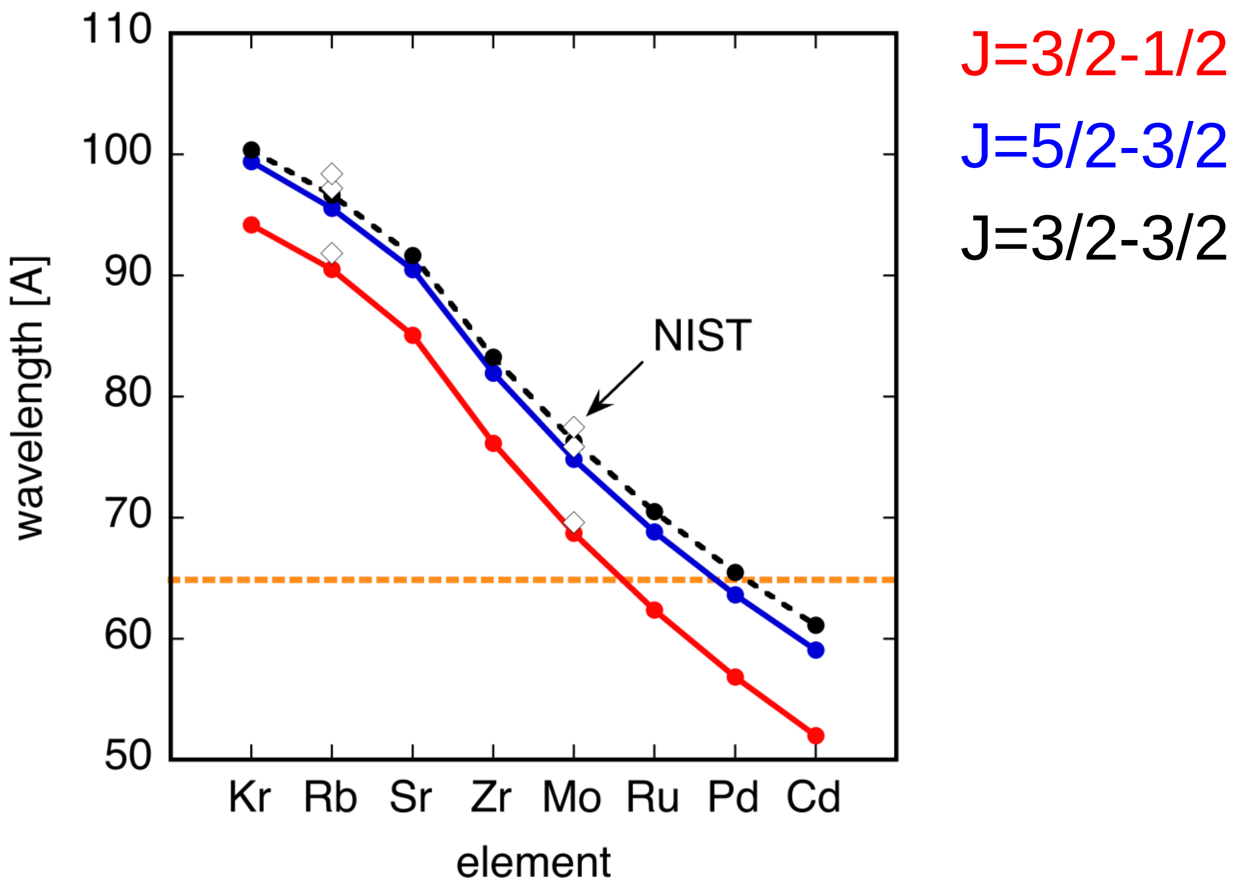
Summary

- Atomic model is improved after nLTE workshops.
- 3p-3d transition seems promising for the 6.5nm source.

  - Kr is shown to be NOT useful for 6.5nm source.
  - 6.5nm emission can be obtained from 3p-3d transition of ions with Z=40 - 50.
  - 3p-3d transition has a property similar to 4d-4f.
  - Using Co-like Mo^{15+}, spectral efficiency>1% at λ=6.8nm into 0.5% BW is expected.
  - Simultaneous optimization of target material and coating is required.

Wavelength of Co-like 3p-3d transitions

- Co-like transition consists of 3 fine structure lines; wavelength decreases 0.6nm per atomic number.
- Accuracy of calculated wavelength is 2%.



Future work

- Another subjects of fundamental physics should be studied if high power 13.5nm source is higher priority than 6.5nm source.

  - Modeling radiation hydrodynamics.

  - Modeling laser ablation; interaction of laser between warm dense matter decides the profile of the plasma and performance of the source.

  - Laser physics; difficulties in increasing laser power (thermal effects, stochastic failure) thought as technical but may have physical reason.